Public Works Canada
Solar Programs Office

Travaux publics Canada
Bureau des programmes solaires

Public Works Canada
Solar Programs Office

ASTEP USER'S MANUAL

VERSION 1.0

January 1984

Prepared for:

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1.0

SYSTEM OVERVIEW

ASTEP is a solar heating system design program, developed at the University of Toronto, which permits the hourly simulation of both liquid and air-based solar heating systems for space and service water heating. The program is primarily directed to the analysis of seasonal storage systems, although options are included to permit the simulation of short term storage systems as well as a combined seasonal storage and short term storage system.

ASTEP includes a unique procedure for calculating the heat loss from an in-ground seasonal thermal storage tank. The method retains the order of accuracy associated with the more detailed finite-difference calculations, yet does not require the associated restrictive memory requirements and computer time. An additional feature unique to ASTEP is the provision for two different types of meteorological inputs, the Public Works Canada database (DPW) and the precalculated Atmospheric Environment Service database (AES). The DPW database includes values for global solar radiation on a horizontal surface from which the incident solar radiation on a tilted solar collector surface must be calculated within ASTEP using established models. The AES database includes precalculated values for incident solar radiation on selected tilt angles of 30, 60, and 90 degrees based on procedures adopted by the Canadian Atmospheric Environment Service, from which the incident solar radiation on a surface of

specified tilt is calculated simply by interpolation within ASTEP.

An overview of the implementation of the ASTEP interactive program showing the possible inputs and outputs is shown in Figure 1.1.

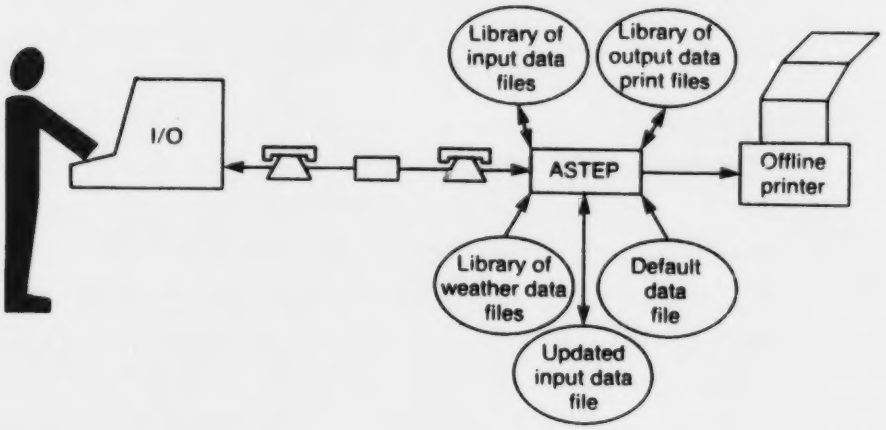


Figure 1.1 ASTEP interactive program

1.1 Systems Modelled

ASTEP provides for the modelling of up to ten different solar heating systems.

1. Seasonal Storage Liquid Based
2. Seasonal Storage Liquid Based With Heat Pump
3. Seasonal Storage Air Based
4. Seasonal Storage Air Based With Heat Pump
5. Short Term Storage Liquid Based
6. Short Term Storage Liquid Based With Heat Pump
7. Short Term Storage Air Based
8. Short Term Storage Air Based With Heat Pump
9. Seasonal And Short Term Storage Liquid Based
10. Seasonal And Short Term Liquid Based With Heat Pump

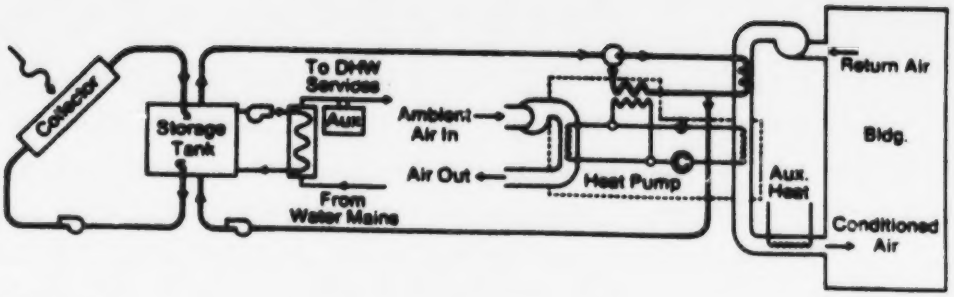
These systems comprise three basic design types, as shown schematically in Figure 1.2. Type I uses a liquid heat transport and storage fluid in conjunction with a single thermal storage tank. Type II uses air as the transport fluid in conjunction with a single rock bed thermal storage arranged for reversible air flow. Type III is another liquid transport and storage system, but incorporating two storage tanks and able to store heat on both short term and seasonal cycles. Types I and II can both have storages sized to provide either short term or seasonal storage. All three design types incorporate a heat pump option with either a single or a dual source evaporator.

For each system, the simulation proceeds in an hourly stepwise fashion, assuming within any given hour that the weather inputs such as outside dry bulb temperature and solar irradiance, and other system parameters such as hot water storage temperature and building energy demand, can be considered to be constant. This reduces the time dependent differential equations associated with the thermal performance of the sysem to the corresponding simpler set of algebraic equations which can be solved explicitly. Energy transfers are computed in the sequence of collector heat gain, service hot water demand, space heating load, and storage heat loss.

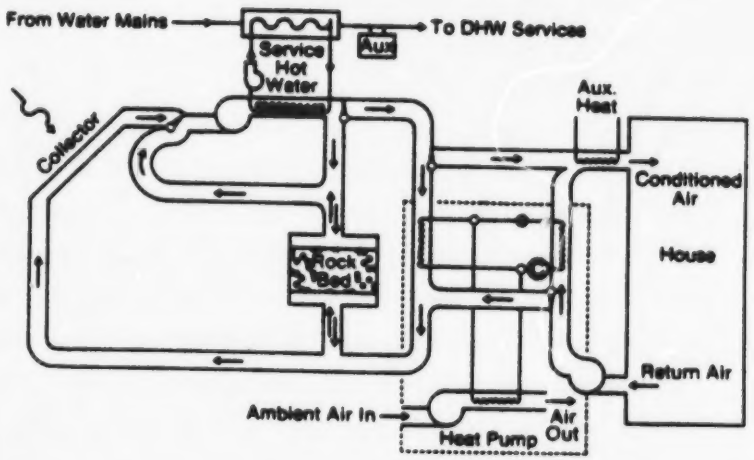
The input parameters for each of the solar heating systems are outlined in Chapter 4 and a description of the thermal models and assumptions is provided in Chapter 6.

1.1.1 Type I - Liquid

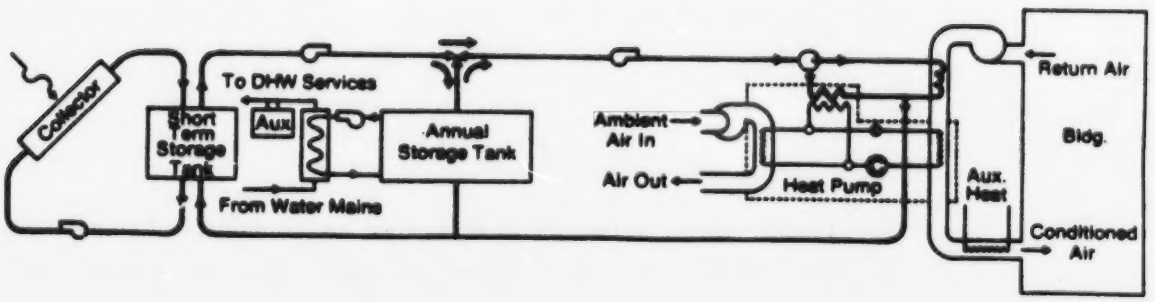
The liquid-based solar heating system is conceptually the simplest of the three designs. Shown schematically in Figure 1.2, it consists primarily of three independent loops, identified as the collection loop, the space heating loop and the service hot water loop, sharing the same thermal storage. An optional heat pump loop is included to provide assistance in meeeting the heat load



Type I



Type II



Type III

Figure 1.2 ASTEP Basic System Types

when the storage temperature falls below some predetermined temperature as specified by the user. The characteristics and control strategies of the components within each of these loops are described in Chapter 6.

1.1.2 Type II - Air

The air-based solar heating system, shown schematically in Figure 1.2, utilizes a reversible flow rock bed thermal storage. There are three possible modes of operation. These are:

A) Charge Mode - Thermal charging of the storage occurs only after all building heat loads are met and while useful heat output is available from the collector. Air flow through the storage during charging is from top to bottom.

B) Discharge Mode - Thermal discharge from the storage occurs when there is a building heat load but an insufficient useful heat output from the collector. Air flow through the storage is from bottom to top, the reverse of that for the charge mode. A heat pump option is included to assist in meeting the heat load when the storage temperature falls below some user-specified temperature.

C) Direct Mode - Direct heating from the solar collector is provided when useful heat output from the collector occurs simultaneously with a building heat load.

1.1.3 Type III - Two-tank

The two-tank solar heating system, shown schematically in Figure 1.2, includes both seasonal storage and short term storages

operating together. It has been modelled in ASTEP for liquid based systems only.

Output from the collector is stored in the short term storage tank. If the temperature of this tank is greater than that of the larger tank, and exceeds it by more than some control temperature difference specified by the user, then heat is transferred from the short term tank to the larger seasonal storage tank.

The first priority in meeting the building heat loads is from the short term tank. When the stored heat has been drained from this tank, heat is drawn from the larger tank. The service hot water load is taken from the seasonal storage tank when it can provide a greater portion of the load then the short term tank.

2.0

GETTING STARTED

To acquaint yourself with ASTEP, sit down at a terminal and run through the tutorial given in this chapter. This will introduce you to the commands needed to operate ASTEP, including the creation of an input data file and the saving of output results from a simulation run. More detailed information on the various commands is provided in chapter 3.

2.1 Tutorial Session

For this tutorial, your responses appear in italics. First of all, start the program by simply typing the command ASTEP. The program responds with the following display.

astep

WELCOME TO ASTEP 1.0

DEVELOPED BY

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FOR PUBLIC WORKS CANADA 1984

```
SELECT ONE OF THE OPTIONS AND ENTER
    CREATE    RUN    PRINT    SAVE    MODIFY    GET
    ERASE     HELP   LIST     LISTC   TYPE      EXIT
```

The command HELP can be used at anytime to provide a brief explanation of each command option as follows:

```
help
FOLLOWING IS A BRIEF EXPLANATION OF COMMANDS
CREATE     CREATES A NEW DATA FILE USING INTERACTIVE PROGRAM
RUN        EXECUTES ASTEP SIMULATOR USING A DATA FILE
PRINT      PRINTS LISTING FILE
SAVE       SAVES DATA OR LISTING FILE
MODIFY     MODIFIES AN EXISTING DATA FILE INTERACTIVELY
GET        LOADS AN EXISTING DATA FILE INTO MEMORY
ERASE      ERASES A DATA OR LISTING FILE
HELP       PROVIDES A BRIEF EXPLANATION OF COMMANDS
LIST       LISTS DATA AND LISTING FILE NAMES
LISTC      LISTS CITY NAMES FOR WHICH WEATHER DATA IS AVAILABLE
TYPE       TYPES LISTING FILE ON TERMINAL
EXIT       EXITS FROM THE INTERACTIVE ASTEP PROGRAM

 SELECT?
```

As a first time user, you will need to prepare an input data file containing the system parameters required to describe your system to ASTEP. This is accomplished using the CREATE command.

```
 SELECT?create

  Enter system name OR hit RETURN for list of systems
```

By hitting the return key, you will display a list of systems currently available within ASTEP.

```
  Following systems are currently available under ASTEP
  interactive system


      1 SEL  Seasonal Storage Liquid Based
      2 SELH Seasonal Storage Liquid Based With Heat Pump
      3 SEA  Seasonal Storage Air Based
      4 SEAH Seasonal Storage Air Based With Heat Pump
      5 SHL  Short Term Storage Liquid Based
```

```
 6 SHLH Short Term Storage Liquid Based With Heat Pump
 7 SHA  Short Term Storage Air Based
 8 SHAH Short Term Storage Air Based With Heat Pump
 9 SSL  Seasonal And Short Term Storage Liquid Based
10 SSLH Seasonal  And  Short  Term  Liquid  Based  With  Heat  Pump

  Enter System name OR hit RETURN for list of systems
```

For this example, specify a seasonal storage liquid based system by entering the system name SEL.

sel

```
  Require a system description?  (Y/N)
```

A short description of the system is provided by entering Y.

y

```
A liquid based seasonal storage solar heating system for space
and hot water heating.  The system consists  primarily of  three
independent  loops,  collection,  space  heating,  and  hot  water
heating, sharing a single subsurface seasonal heat storage
reservoir.

 Enter any character to continue, or
 Enter MORE (to examine other systems) or EXIT
```

By entering any character and hitting RETURN, the program responds with the following prompt.

```
  Command?
```

Your are now ready to create your input data file. For a list of the available subcommands, enter the subcommand HELP.

help

```
 Command              Description
  HELP      Display this list of command descriptions
  AUTO      Enter automatic mode for data entry
  TITLe     Enter or modify a title line
  QUIT      Quit and enter Command? level
```

```
  SKIP     Skip interactive program and save changes
  EXIT     Exit interactive program without saving changes

 Current System Name is - SEL

 Data Blocks required for the system are -
  SIMULATION
  COLLECTOR
  SEASONAL STORAGE
  BUILDING

 Command?
```

The input parameters needed to describe the system are grouped into blocks. The seasonal storage liquid based system (SEL), chosen for this example, requires four blocks; Simulation, Collector, Seasonal Storage, and Building. At this point in the program, default values have been assigned to the parameters in each of these blocks. You may now examine these values and make changes by using either the AUTO subcommand, whereby the data blocks are automatically displayed one-by-one, or by entering the first four characters of the name for the particular data block you want to examine. Since this is the first time you are creating an input data file, use the AUTO command to display the first block of data.

auto

* SIMULATION

Item	Description	Value	Units
1	Start Day Number (1-31).....	1.0000	day
2	Start Month Number (1-12).....	4.0000	month
3	Start Year (last 3 digits).....	970.00	year
4	Final Day Number (1-31).....	31.000	day
5	Final Month Number (1-12).....	3.0000	month
6	Hourly Output (1=yes,0=no).....	0.00000E+00	
7	Daily Output (1=yes,0=no).....	0.00000E+00	
8	Monthly Output (1=yes,0=no).....	0.00000E+00	
9	System Number (1-10).....	1.0000	
10	Weather Data Format (1=DPW,2=AES).....	2.0000	
11	Weather Year Type (1=consecutive, 2=wrap).....	2.0000	
12	Final Year of Weather File (last 3 digits).....	970.00	year

Enter item no. & new value

Each of the parameters is identified by an item number which must be used when making changes. A change is made by simply specifying the item number followed by the new value. These can be separated by any number of spaces or a comma. To change the weather data format (Item 10) from AES to DPW, enter the following.

10 1

You have now changed the value of the weather data format parameter. Any number of additional changes can be similarly entered. The program checks that the new value for the parameter is within a certain internally defined range. If the new value is outside this range, a warning message will appear. For example, enter the value of 3 for the weather data format item as follows.

10 3

Warning. Value for SIMU Item 10 outside range (1.00 to 2.00).

The new value is outside the set range and a warning message is displayed, identifying the limits. Even though a warning is given, the value is retained until you change it so that it is possible to continue and attempt to make a simulation run using this value. In this case the simulation would not run with this value for the weather data format.

For some parameters, the simulation would run but the results may be misleading if the value is outside the defined limits. To correct the value of Item 10 enter the following.

10 1

Once all changes have been finalized, enter QUIT to allow you to go on to the next input data block.

quit

```
 * COLLECTOR
    Item    Description                                  Value      Units

       1  Area.....................................  240.00       m2
       2  Differential Temperature Control On...   6.0000       C
       3  Differential Temperature Control Off..   3.0000       C
       4  Fr-Tau-Alpha Product..................  0.75000
       5  Fr-Ul per Unit Area...................   5.0000       W/m2-C
       6  Tilt from horizontal..................   60.000       deg.
       7  Azimuth(0=south,+=east)...............  0.00000E+00  deg.
       8  Horizontal Reflector Area.............  0.00000E+00  m2
       9  Reflector Configuration Factor (0-1)..  0.10000
      10  DeWinter Heat Exchanger Factor (0-1...  1.0000
      11  Incidence Angle Modifier.Angle Values.  0.00000E+00
      12  Incidence Angle Modifier..AKT Values..  0.00000E+00

  Enter item no. & new value
```

Some of the parameter items in ASTEP are associated with a group of values. For example, there are five data pairs associated with the incidence angle modifier items 11 and 12. These parameters are used to calculate the incidence angle modifier for any value of the direct beam incidence angle using a cubic spline interpolation. For each angle value of item 11 there is a corresponding modifier value from item 12. To examine or edit the values of items 11 or 12, enter the item number followed by either a 1, if you are editing a single element, or a 2 if you are editing all of the elements, as illustrated here.

11 1

```
  Code Value  Code Value  Code Value  Code Value  Code Value

    1 0.00E+00  2 0.30E+02  3 0.45E+02  4 0.60E+02  5 0.90E+02

 Enter code number and new value, or enter QUIT
 Sum of elements in the profile is 0.23E+03
```

```
quit
11 2

   Values are
      0.000E+00    0.300E+02    0.450E+02    0.600E+02    0.900E+02

  Enter 5 values, or enter QUIT
  Sum of elements in the profile is 0.23E+03

quit
12 1

   Code Value  Code Value  Code Value  Code Value  Code Value

     1 0.10E+01  2 0.10E+01  3 0.97E+00  4 0.87E+00  5 0.00E+00

  Enter code number and new value, or enter QUIT
  Sum of elements in the profile is 3.8

quit
12 2

   Values are
      0.100E+01    0.100E+01    0.970E+00    0.877E+00    0.000E+00

  Enter 5 values, or enter QUIT
  Sum of elements in the profile is 3.8

quit
```

For this example run, all of the default values for this block will be used. Enter QUIT to go on to the next block.

```
quit

 * SEASONAL STORAGE
    Item     Description                                  Value    Units

       1  Volume.....................................  900.00   m3
       2  Depth......................................  6.5000   m
       3  Density....................................  1600.0   kg/m3
       4  Thermal Capacitance........................  4.1860   kJ/kg-C
       5  Initial Storage Temperature................  30.000   C
       6  Maximum Allowable Storage Temperature...  90.000   C
       7  Temperature Gradient Factor................  2.5000   C
       8  Location (1=outdoor,2=indoor).............  1.0000
       9  R-value of Tank Insulation.................  5.0000   m2-C/W
```

10	R-value of Tank Lid Insulation.....	5.0000	m2-C/W
11	Isothermal Watertable Depth.....	9.7500	m
12	Soil Thermal Conductivity.....	1.7300	W/m-C
13	Soil Density.....	2000.0	kg/m3
14	Soil Thermal Capacity.....	1.0000	kJ/kg-C
15	Normalized Soil R-value (RNORM - See Manual).....	0.10000	m-C/W
16	Lumped Heat Sink Partition (BETA - see Manual).....	0.48600	
17	Storage Temperature Cycle - High Temperature.....	80.000	C
18	Storage Temperature Cycle - Low Temperature.....	30.000	C

Enter item no. & new value

Again, the default values for this block will be used for your test run. Enter QUIT to go on to the next block.

quit

* BUILDING

Item	Description	Value	Units
1	Indoor Design Temperature.....	21.000	C
2	Effective Temperature for Space Heating.	18.000	C
3	Space Heat Load Factor.....	5000.0	kJ/C-hr
4	Minimum Storage Temperature for Space Heating.....	30.000	C
5	Water Mains Temperature.....	10.000	C
6	Hot Water Set Temperature.....	50.000	C
7	DHW Heat Exchanger Temperature Drop.....	2.5000	C
8	Number of Days for Load Profile(1) (0-7)	7.0000	
9	Daily Hot Water Load for Load Profile (1)	1548.0	kg/day
10	Daily Hot Water Load for Load Profile (2)	1548.0	kg/day
11	Daily Hot Water Load Profile (1).....	100.00	percent
12	Daily Hot Water Load Profile (2).....0.00000+00		percent

Enter item no. & new value

The daily hot water load profiles (items 11 and 12) are of particular interest here. These parameters allow you to define two different hot water hourly load profiles. Each item is therefore associated with 24 values. These values are edited in a similar fashion as the incidence angle modifiers for the collector block.

```
11 1

  Code Value  Code Value  Code Value  Code Value  Code Value

    1 0.22E+01  2 0.00E+00  3 0.00E+00  4 0.00E+00  5 0.00E+00
    6 0.00E+00  7 0.15E+01  8 0.46E+01  9 0.72E+01 10 0.84E+01
   11 0.69E+01 12 0.45E+01 13 0.36E+01 14 0.51E+01 15 0.27E+01
   16 0.24E+01 17 0.21E+01 18 0.37E+01 19 0.67E+01 20 0.11E+02
   21 0.96E+01 22 0.69E+01 23 0.54E+01 24 0.46E+01

  Enter code number and new value, or enter QUIT
  Sum of elements in the profile is  0.10E+03


quit
11 2


   Values are
      0.225E+01 0.000E+00 0.000E+00 0.000E+00 0.000E+00
      0.000E+00 0.150E+00 0.465E+01 0.725E+01 0.849E+01
      0.690E+01 0.450E+01 0.360E+01 0.510E+01 0.270E+01
      0.240E+01 0.210E+01 0.375E+01 0.675E+01 0.111E+02
      0.960E+01 0.690E+01 0.546E+01 0.465E+01

  Enter 24 values, or enter QUIT
  Sum of elements in the profile is  0.10E+03


quit
```

For this test run, the default values for this block will be used. Enter QUIT to complete your new input data file.

```
quit


  Input is complete.  Use SKIP to save changes.


  Command?
```

The SKIP subcommand can now be entered to save any changes that you have made to permit you to perform a simulation run with your new input data file.

```
skip
```

```
 SELECT?
```

You are now back in the main command level and your input data are temporarily saved. To save the data permanently in your library, use the SAVE command as follows.

```
 SELECT?save data tor1
DATA SAVED ON TOR1

 SELECT?
```

Your new input data set is now permanently stored in your library for future use under the name TOR1. To perform a test run using the new data, simply use the RUN command.

```
 SELECT?run

DATA FILE LAST UPDATED WILL BE USED FOR THE RUN

ENTER CITY WEATHER FILE NAME OR HIT RETURN TO ABORT.
( FOR A LIST OF WEATHER FILE NAMES ENTER AES OR DPW )
```

Since the weather data format parameter is set to DPW for this test run, enter DPW for a list of available stations.

```
dpw
```

PUBLIC WORKS CANADA DATABASE

CITY	YR	FILE	CITY	YR	FILE	CITY	YR	FILE
PRINCE G BC	74	PRIN	KAPUSKAS ON	66	KAPU	CHARLO ND	71	CHAR
SUMMERLA BC	71	SUMM	KINGSTON ON	71	KING	CHATHAM ND	71	CHAT
VANCOUVE BC	71	VANC	LONDON ON	71	LOND	FREDERI ND	71	FRED
VICTORIA BC	71	VICT	MUSKOKA ON	71	MUSK	MONCTON ND	71	MONC
FRODIS D NT	75	FROD	OTTAWA ON	71	OTTO	SAINT J ND	71	SJHN
RESOLUT NT	71	RESO	SAULT ST ON	71	SAUL	CHARLOT PE	71	CHAR
EDMONTON AL	71	EDMO	SUDBURY ON	71	SUDB	HALIFAX NS	71	HALI
MEDICI H AL	71	MEDI	THUNDE B ON	71	THUN	SYDNEY NS	71	SYDN
SASKATOO SA	71	SASK	TORONTO ON	71	TORO	TRURO NS	71	TRUR
SWIFT CU SA	71	SWIF	WINDSOR ON	71	WIND	YARMOUT NS	71	YARM
URANIU C SA	71	URAN	BAGOTVIL QU	71	BAGO	GANDER NF	71	GAND
BRANDON MA	71	BRAND	MONTREAL QU	71	MONT	GOOSE NF	71	GOOS
CHURCHIL MA	75	CHUR	QUEBEC QU	71	QUEB	ST.JOHN NF	71	SJHS
THE PAS MA	71	THEP	RIVIER D QU	71	RIVI	STEPHEN NF	71	STEP
WINNIPEG MA	71	WINN	SEPT ILS QU	74	SEPT	VAL DOR QU	71	VALD
			SHERBROO QU	71	SHER			

```
ENTER CITY WEATHER FILE NAME OR HIT RETURN TO ABORT.
( FOR A LIST OF WEATHER FILE NAMES ENTER AES OR DPW )
```

For this test run, choose the city of Toronto, Ontario. Enter the filename TORO and the latitude in response to the prompt. The annual performance summary for the system simulation will then be displayed.

```
toro

Enter latitude of city (degrees): 44

**********************************************************************

ASTEP SIMULATION RESULTS - ANNUAL PERFORMANCE SUMMARY

          BUILDING                              COLLECTOR
BLDG HEATING PERFORMANC 67.30 %  COLLECTOR EFFICIENCY     42.32   %
DHW HEATING PERFORMANCE 69.93 %  COLLECTED SOLAR ENERGY  516656 MJ
TOTAL SYSTEM PERFORMANC 67.71 %  INCIDENT SOLAR ENERGY  1220837 MJ
DEGREE DAYS BASE 18.0 C  4126    REJECTED SOLAR ENERGY       0 MJ
MEAN OUTDOOR TEMPERATURE 7.16 C  COLLECTOR OPERATING TIME  1902 MR
SPACE HEATING LOAD     507578 MJ            STORAGE
SOLAR SPACE HEAT       341582 MJ
AUXILIARY SPACE HEAT   165996 MJ  MAX STORAGE TEMP SEP 11 56.16 C
HOT WATER LOAD          94275 MJ  MEAN STORAGE TEMP       40.96 C
SOLAR HOT WATER         65927 MJ  MIN STORAGE TEMP FEB 25 29.66 C
AUXILIARY HOT WATER     28348 MJ  STORAGE HEAT LOSS      107657 MJ
                                  LID HEAT LOSS           29515 MJ
                                  UNDERGROUND HEAT LOSS   78142 MJ
----------------------------------------------------------------------

 SELECT?
```

After examining the results of the first simulation run you can go back and update your input data file and rerun the simulation. Begin by using the MODIFY command. This command supports the same subcommands as the CREATE command.

```
 SELECT?modify

DATA FILE LAST USED WILL BE MODIFIED
```

Current System Name is - SEL
Do you wish to change System Name? (Y/N)

Since you are not making a system change at this point enter N.

n

Command?

You can now make any changes directly by entering the data block name followed by the parameter item number and the new value. To change the collector area, enter the following.

coll 1 300

Command?

Once all changes have been made, the SKIP subcommand is used to save temporarily the new file.

skip

SELECT?

A new simulation run can now be performed by using the run command as before.

SELECT?*run*

DATA FILE LAST UPDATED WILL BE USED FOR THE RUN

ENTER CITY WEATHER FILE NAME OR HIT RETURN TO ABORT.
(FOR A LIST OF WEATHER FILE NAMES ENTER AES OR DPW)

toro

Enter latitude of city (degrees): *44*

```
**********************************************************************

ASTEP SIMULATION RESULTS - ANNUAL PERFORMANCE SUMMARY
          BUILDING                              COLLECTOR
BLDG HEATING PERFORMANC 80.26 %  COLLECTOR EFFICIENCY     39.48   %
DHW HEATING PERFORMANCE 75.85 %  COLLECTED SOLAR ENERGY  602472 MJ
TOTAL SYSTEM PERFORMANC 79.57 %  INCIDENT SOLAR ENERGY 1526046 MJ
DEGREE DAYS BASE 18.0 C  4126    REJECTED SOLAR ENERGY       0 MJ
MEAN OUTDOOR TEMPERATURE 7.16 C  COLLECTOR OPERATING TIME 1816 HR
SPACE HEATING LOAD     507578 MJ            STORAGE
SOLAR SPACE HEAT       407366 MJ
AUXILIARY SPACE HEAT   100212 MJ  MAX STORAGE TEMP OCT 04 63.36 C
HOT WATER LOAD          94275 MJ  MEAN STORAGE TEMP       45.44 C
SOLAR HOT WATER         71510 MJ  MIN STORAGE TEMP FEB 25 29.67 C
AUXILIARY HOT WATER     22765 MJ  STORAGE HEAT LOSS      121518 MJ
                                  LID HEAT LOSS           33424 MJ
                                  UNDERGROUND HEAT LOSS   88094 MJ

----------------------------------------------------------------------

 SELECT?
```

To save the simulation results permanently in your library, use the SAVE command.

```
 SELECT?save listing tor2
OUTPUT SAVED ON TOR2
```

Similarly, you can save the most recent updated input file as follows.

```
 SELECT?save data tor2
DATA SAVED ON TOR2
```

Once you are finished with ASTEP, use the EXIT command. Input files and output results that have been stored in you library will be retained for future use.

```
 SELECT?exit
GOODBYE.  TYPE <LOGOFF> IF FINISHED ELSE TYPE ASTEP
READY
logoff
```

3.0

COMMAND LANGUAGE

This chapter describes the commands and subcommands of the ASTEP program that allow the user to interact with the various data files and the simulation program. The command language used in the ASTEP program is modelled after the WATSUN 5.0 interactive program in an attempt to minimize the period of familiarization when using either of the programs.

3.1 Format

A command consists of a command name followed, usually, by one or more operands in a prescribed sequence, separated by spaces. For example, the operands for the RUN command identify the name of the input data file to be used for the simulation and the file name of the city for which the simulation is to be performed:

```
RUN test toro
```

If no operands are specified, the user is prompted for the necessary information. A brief summary of the available commands is outlined in Table 3.1. A more detailed description of each command is provided in section 3.2.

TABLE 3.1

ASTEP Command Language

Command Name	Function	Operands[1]
CREATE	- create a new input data file	
ERASE	- erase an input data file or simulation results listing file.	{DATA,LISTING}, file-name
EXIT	- exit from ASTEP program.	
GET	- load an existing input data file into memory.	data-file-name
HELP	- provide a brief explanation of commands.	
LIST	- list input data files and/or simulation results listing files.	{DATA, LISTING}
LISTC	- list city names for which weather data are available.	{AES, DPW}
MODIFY	- modify an existing input data file.	data-file-name
PRINT	- print simulation results listing file offline.	listing-file-name
RUN	- execute ASTEP simulation	data-file-name, city-file-name
SAVE	- save input data file or simulation results listing file for future use.	{DATA, LISTING}, file-name
TYPE	- display simulation results listing file at terminal.	listing-file-name

[1] Braces ({}) indicate that only one of the alternatives should be specified.

3.2 Command Descriptions

CREATE

The CREATE command is used to create a new input data file containing parameter values that describe the particular solar heating system. There are no operands for this command. The user is prompted to select one of ten different solar heating systems, for whch a brief system description may be obtained. When the program prompt "Command?" appears, the user may enter any one of the available subcommands. A brief description of each subcommand is obtained by entering the HELP subcommand. The following subcommands are available:

AUTO - Enter special data entry mode whereby the user is prompted for data input for each parameter block in sequence. Default value are assigned to all of the parameters of each block. Changes to these values may be input by entering the block item number and the new value, separated by a space. Only one change may be made for each line of entry. Any number of line entries can be made. The parameter values may be reviewed at any time by entering the first four characters of the parameter block name. To procede to the next parameter block, the user must enter the QUIT subcommand.

EXIT - Return to the main command level without saving any input data file modifications.

HELP - Displays a brief description of each subcommand and also identifies the current solar heating system and the required parameter data blocks.

QUIT - Proceed to next parameter data block or terminate profile entry mode.

SKIP - Return to main command level saving all input data file modifications.

TITLE - Specify title to identify simulation results.

Data Block Name - Direct method of data entry. A time-saving alternative to the use of the AUTO subcommand. Enter the first four characters of the data block name followed by any number of data pairs consisting of the block item number and the new value. (i.e. COLL 1,100 2,10 3,1)

ERASE {DATA, LISTING} filename

The ERASE command is used to delete a file from either the library of input data files or the library of simulation results listing files. If the operands are omitted, the user is prompted for the necessary information. The libraries should be cleared regularly by deleting unwanted files and compressing the existing files. The LIST command may be used to examine existing library files.

EXIT

The EXIT command is used to exit from the ASTEP program. The user may then log-off from the computer or enter ASTEP to restart the program.

GET data-file-name

The GET command is used to load an existing input data file from the library into memory as a temporary file for use with the RUN and MODIFY commands. If the file name is omitted the user will be prompted for this information. Note that the RUN and MODIFY commands can directly bring data files into memory without using the GET command.

HELP

The HELP command is used to obtain a brief explanation for each command.

LIST {DATA, LISTING}

The LIST command is used to obtain a list of existing files that have been saved in the input data library or the simulation results library. If the operand is omitted, a table of file names for both libraries is provided.

LISTC {AES, DPW}

The LISTC command is used to obtain a list of available weather data files in either the AES format (includes pre-calculated tilt solar radiation) or the DPW format (includes horizontal solar radiation). The weather data file names are identified by the first four characters of the city name.

MODIFY data-file-name

The MODIFY command is used to edit an existing input data file. If the name of an existing input data file is omitted, the current temporary input data file will be used. The user is prompted to select a different solar heating system if required. Once the prompt "Command?" appears, the user may enter any one of the subcommands described for the CREATE command.

PRINT listing-file-name

The PRINT command is used to print the listing file containing the simulation results offline at the computing centre. The printout contains a list of input data as well as performance results. If the file name is omitted, the user is prompted for the information. The name of the temporary listing file containing the results of the most recent simulation is LISTING.

RUN data-file-name city-file-name

The RUN command is used to execute the ASTEP simulation. If the operands are omitted, the input data file last updated is used and the user is prompted for a city file name. The LISTC command may be used to obtain a list of four character file names for cities for which weather data are available.

SAVE {DATA, LISTING} file-name

The SAVE command is used to save a file into a library for future reference. If the operands are omitted, the user is prompted for the necessary information. the LIST command may be used to examine existing library files.

TYPE listing-file-name

The TYPE command is similar to the PRINT command except that the print file is displayed at the terminal. If the file name is omitted, the user is prompted for the information.

4.0

INPUT PARAMETERS

The system input parameters are divided into eight groups or data blocks.

1. Simulation
2. Collector
3. Seasonal Storage
4. Short Term Storage
5. Dual Storage
6. Rock Bed
7. Building
8. Heat Pump

For the particular solar heating system selected, the appropriate data blocks are automatically assembled into one input data file for editing or simulation. A list of the required data blocks for each of the ten ASTEP solar heating sstems is provided in Table 4.1.

Each parameter within a data block is automatically assigned a default value and a range. If the value of a parameter lies outside the specified range, a warning message appears. The value of the parameter is, however, retained until corrected. In some cases, the range specified corresponds to the practical limits of the models used, and values outside this range may affect the accuracy of the simulation results. This does not, however, prevent the simulation from proceeding. In other cases, the range

TABLE 4.1

Input Data Block Requirements for ASTEP Solar Heating Systems

System	Description	Data Blocks[1] 1	2	3	4	5	6	7	8
SEL	Seasonal storage liquid based	*	*	*				*	
SELH	Seasonal storage liquid based with heat pump	*	*	*				*	*
SEA	Seasonal storage air based	*	*	*			*	*	
SEAH	Seasonal storage air based with heat pump	*	*	*			*	*	*
SHL	Short term storage liquid based	*	*		*			*	
SHLH	Short term storage liquid based with heat pump	*	*		*			*	*
SHA	Short term storage air based	*	*		*		*	*	
SHAH	Short term storage air based with heat pump	*	*		*		*	*	*
SSL	Seasonal and short term storage liquid based	*	*	*	*	*		*	
SSLH	Seasonal and short term liquid based with heat pump	*	*	*	*	*		*	*

[1] 1 = Simulation
2 = Collector
3 = Seasonal Storage
4 = Short Term Storage
5 = Dual Storage
6 = Rock Bed
7 = Building
8 = Heat Pump

includes all the acceptable values for a parameter, and a value outside this range does prevent the simulation from proceeding. A detailed description of each data block, including the default value for each parameter, is provided in section 4.1 - 4.8 which follow.

4.1 Simulation

The Simulation data block contains information about the simulation period, the weather data, and the format of the simulation results.

Item	Description	Default	Units
1	Start Day Number (1-31).....	1.0	day
2	Start Month Number (1-12).....	4.0	month
3	Start Year (last 3 digits).....	970.0	year
4	Final Day Number (1-31).....	31.0	day
5	Final Month Number (1-12).....	3.0	month
6	Hourly Output (1=yes,0=no).....	0.0	
7	Daily Output (1=yes,0=no).....	0.0	
8	Monthly Output (1=yes,0=no).....	0.0	
9	System Number (1-10).....	1.0	
10	Weather Data Format (1=DPW,2=AES).....	2.0	
11	Weather Year Type (1=consecutive,2=wrap).....	2.0	
12	Final Year of Weather File (last 3 digits)...	970.0	year

Item Notes

3. The AES database includes data for the ten year period 1967-76, while the DPW database contains only one year of data, usually for 1971. The value of the Start Year parameter is disregarded when using the DPW database.

10. Two different types of meteorological inputs are available. Refer to Chapter 5 Weather Data for further explanation.

11. Simulations can proceed past the end of the year by either continuing into the following year (consecutive) or

continuing from the beginning of the same year (wrap). The consecutive option is of course only available when using the multi-year AES database.

12. 1976 is the final year of weather data available for the AES database. The value of this parameter is disregarded when using the DPW database.

4.2 Collector

The Collector data block contains information about the collector performance parameters, including incidence angle modifiers, and the position of the collectors.

Item	Description	Default	Units
1	Area	240.0	m^2
2	Differential Temperature Control On	6.0	C
3	Differential Temperature Control Off	3.0	C
4	Fr-Tau-Alpha Product	0.75	
5	Fr-Ul per Unit Area	5.0	w/m^2-C
6	Tilt from horizontal	60.0	deg.
7	Azimuth (0=south,+=east)	0.0	deg.
8	Horizontal Relector Area	0.0	m^2
9	Reflector Configuration Factor (0-1)	0.1	
10	DeWinter Heat Exchanger Factor (0-1)	1.0	
11	Incidence Angle Modifier..Angle Values	0.0	
	0.0 30.0 45.0 60.0 90.0		
12	Incidence AnglModifier..AKT Values	0.0	
	1.000 1.000 0.970 0.877 0.000		

Item Notes

4,5. The y-intercept and slope, respectively, of a collector efficiency curve based on the collector inlet fluid temperature, supplied by the manufacturer. Refer to Lunde (1980) for techniques to transform collector efficiency curves based on the outlet fluid temperature or mean fluid temperature.

7. At present, the azimuth position must be set to one of either -180, -90, -45, 0, 45, 90, or 180 when using the AES database.

8. A horizontal diffuse reflector in front of the collectors is assumed.

9. A useful reference of radiant-interchange configuration factors between plane surfaces is provided by Feingold (1966).

10. A heat exchanger correction factor is used to modify the collector performance equation to account for the effects of a heat exchanger between the collector and storage. Refer to DeWinter (1975).

11,12. AKT values for the angles shown are normally available from tests performed at the National Solar Simulator Facility located at the Ontario Research Foundation. The values can be modified by entering the item number and either the number '1' or '2'. To return to the data block, the QUIT subcommand must be entered. A cubic spline interpolation of these data is carried out to calculate the incidence angle modifier for any value of the direct beam incidence angle.

4.3 Seasonal Storage

The Seasonal Storage data block contains information relating to the tank dimensions and location, and the thermal characteristics of the heat transfer medium and the surrounding soil. The tank is assumed to be of cylindrical shape, positioned with a vertical axis of symmetry, and buried with the top flush with the ground surface.

Item	Description	Default	Units
1	Volume	900.0	m^3
2	Depth	6.5	m
3	Density	1600.0	kg/m^3
4	Thermal Capacitance	4.186	kJ/kg-C
5	Initial Storage Temperature	30.0	C
6	Maximum Allowable Storage Temperature	90.0	C
7	Temperature Gradient Factor	2.5	C
8	Location (1=outdoor,2=indoor)	1.0	
9	R-value of Tank Insulation	5.0	m^2-C/W
10	R-value of Tank Lid Insulation	5.0	m^2-C/W
11	Isothermal Watertable Depth	9.75	m
12	Soil Thermal Conductivity	1.73	W/m-C
13	Soil Density	2000.0	kg/m^3
14	Soil Thermal Capacity	1.0	kJ/kg-C
15	Normalized Soil R-value	0.1	m-C/W
16	Lumped Heat Sink Partition	0.486	
17	Storage Temperature Cycle-High Temperature	80.0	C
18	Storage Temperature Cycle-Low Temperature	30.0	C

Item Notes

15. The effective unit thermal resistance of the soil, R_s, normalized with tank depth, is used for calculating the storage heat losses. It is a function primarily of the soil thermal conductivity, the tank radius-to-depth rato (R/D), the thermal resistance of the applied insulation (R_I), and the ratio of the depth of the water table to the tank depth (S/D). A large number of tests using a detailed finite difference network was carried out to determine R_s values for a wide range of practical tank configurations. The results are presented in Appendix A.

16. The lumped heat sink partition parameter, β, designates the proportion of the total heat flow through the soil that is lost to the ambient air at the surface of the grund. Beta is a steady state constant for a particular tank-soil configuration, and is independent of the boundary temperatures. Values for β are presented in Appendix A.

4.4 Short Term Storage

The Short Term Storage data block contains information on the tank dimensions and location, and the thermal characteristics of the heat transfer medium. The tank is assumed to be of cylindrical shape, positioned with a vertical axis of symmetry.

Item	Description	Default	Units
1	Volume	10.0	m^3
2	Depth	1.0	m
3	Density	1600.0	kg/m^3
4	Thermal Capacitance	4.186	kJ/kg-c
5	Initial Storage Temperature	30.0	C
6	Maximum Allowable Storage Temperature	90.0	C
7	Temperature Gradient Factor	2.5	C
8	Location (1=outdoor,2=indoor)	2.0	
9	R-value of Tank Insulation	5.0	m^2-C/W

4.5 Dual Storage

The Dual Storage data block contains information on the effectiveness of the heat exchange between the short term storage tank and the seasonal storage tank.

Item	Description	Default	Units
1	Storage Heat Exchanger Temperature Drop	2.5	C

4.6 Rock Bed

The Rock Bed data block contains information about the operation of the reversible flow, rock bed, thermal storage unit.

Item	Description	Default	Units
1	Thermal Capacitance of Air	1.0	kJ/kg-C
2	Thermal Conductivity in Axial Direction	1.73	W/m-C
3	Mass Flow Rate For Collection	5400.0	kg/hr
4	Mass Flow Rate For Heating	5400.0	kg/hr

4.7 Building

The Building data block contains information about the space heating and service hot water loads.

Item	Description	Default	Units
1	Indoor Design Temperature.....	21.0	C
2	Effective Temperature for Space Heating.....	18.0	C
3	Space Heat Load Factor.....	5000.0	kJ/c-hr
4	Minimum Storage Temperature for Space Heating	30.0	C
5	Water Mains Temperature.....	10.0	C
6	Hot Water Set Temperature.....	50.0	C
7	DHW Heat Exchanger Temperature Drop.....	2.5	C
8	Number of Days for Load Profile (1) (0-7)....	7.0	
9	Daily Hot Water Load for Load Profile (1)....	1548.0	kg/day
10	Daily Hot Water Load for Load Profile (2)....	1548.0	kg/day
11	Daily Hot Water Load Profile (1).....	100.0	percent
	2.25 0.00 0.00 0.00 0.00		
	0.00 1.50 4.65 7.25 8.49		
	6.90 4.50 3.60 5.10 2.70		
	2.40 2.10 3.75 6.75 11.10		
	9.60 6.90 5.46 4.65		
12	Daily Hot Water Load Profile (2).....	0.0	percent
	0.0 0.0 0.0 0.0 0.0		
	0.0 0.0 0.0 0.0 0.0		
	0.0 0.0 0.0 0.0 0.0		
	0.0 0.0 0.0 0.0 0.0		
	0.0 0.0 0.0 0.0		

Item Notes

8. If there is a significant difference in the hourly service hot water load profile for different days of the week, such as week days and week ends, two weekly load profiles can be specified.

11,12. The daily hot water load profile consists of the percentages of the total daily load used each hour. The values are listed sequentially across, line by line, beginning at 12:00 midnight. The profile can be modified by entering the item number and either the number '1' or '2'.

To return to the data block, the QUIT subcommand must be entered.

4.8 Heat Pump

The Heat Pump data block contains information about the heat pump performance and limits of operation.

Item	Description	Default	Units
1	Heat Pump COP at 0 deg. C.....	1.25	
2	Slope of COP vs. Evaporator Temperature.....	0.05	1/C
3	Number of evaporators (1-2).....	1.0	
4	Minimum Storage Temperature for Operation....	0.0	C
5	Minimum Air Temperature for Operation.....	0.0	C

Item Notes

1,2. Typical values of COP for a wide range of evaporator temperatures are provided in Chapter 6.

3. An option is included to allow dual evaporators that switch the heat source between the ambient air and the storage in order to select the highest temperature heat source.

5.0

WEATHER DATA

The choice of solar radiation data for simulation purposes has often been limited to total global radiation on a horizontal surface (RF1). Since most of the solar radiation stations measure only RF1, a model is required from which to infer horizontal diffuse radiation (RF2) values. An additional model is required in order to provide the corresponding incident solar energy values for the selected orientation of the solar collector. Several models have been developed to facilitate both of these procedures, varying mainly in their treatment of the diffuse and reflected solar components. The differences are particularly significant for locations in Canada because of the relatively high diffuse solar fractions and the variable albedos typical of the higher latitudes.

A feature unique to ASTEP is the provision for two different types of meteorological inputs, the Public Works Canada database (DPW) and the precalculated Atmospheric Environment Service database (AES). The DPW database includes values for global solar radiation on a horizontal surface, from which the incident solar radiation on a tilted collector surface must be calculated within ASTEP, using established models. The AES database includes precalculated values for incident solar radation on surfaces at selected tilt angles of 30, 60, and 90 degrees, based on procedures adopted by the Canadian Atmospheric Environment Service. From these values the incident solar radiation on a

surface of specified tilt is calculated simply by interpolation within ASTEP. This chapter provides a description of the models and procedures used with each database.

5.1 AES Database

In response to the corresponding increase in demand for reliable hourly solar data, the Canadian Atmospheric Environment Service (AES) undertook in 1979 to expand its solar radiation database (Hooper et al. 1979; McKay and Won 1979). This expansion was carried out in three identifiable phases.

Regular measurements of solar radiation quantities had been made at a number of stations in Canada over significant lengths of time, and the first phase involved synthesizing hourly values of global (RF1) and diffuse (RF2) solar radiation on a horizontal surface for many locations where solar field measurements had not been taken. A mathematical model, known as the MAC3 model, developed by Davies (1980, 1981), was selected that relied on routinely measured meteorological parameters as input. At the time of writing, data for 94 stations across Canada have been processed for the ten-year period 1967 to 1976 using this model.

The second phase involved using this synthesized solar data base for calculating hourly values of the solar radiation components for surfaces tilted at 30°, 60°, and 90° from the horizontal for six aximuth positions, N, W, SW, S, SE, and E. An anisotropic model, developed by Hay (1980), was used for calculating the diffuse radiation term as shown.

$$I_d = H_d[(I\cos(\theta_i))/(I_o\cos(\theta_z)) + 0.5(1.0-I_n/I_o)(1.0 + \cos(\beta))] \qquad 5.1$$

where,

I_d = sky diffuse radiation incident on the slope

H_d = diffuse shortwave radiation on a horizontal surface

I_n = normal incidence direct solar radiation

I_o = extraterrestrial solar radiation
θ_z = solar zenith angle
θ_i = angle that the solar beam makes with the normal to the slope
β = tilt angle of the slope from the horizontal.

The third phase involved providing a complete ten-year solar data base as in the previous phases, but for the locations for which some measured solar data were already available. Gaps in the field measurement of RF1 and RF2, for the period January 1, 1967 to December 31, 1976, were replaced with synthesized data.

This project significantly expanded the existing solar data base by providing a ten-year hourly gap-filled data base suitable for solar and HVAC energy simulation studies for 135 stations across Canada.

The AES weather data elements required as input to ASTEP are listed in table 5.1 ASTEP utilizes the hourly solar and meteorological data directly in the standard AES daily record format for climatological data archived at hourly intervals. Rewriting of the data in a special format is not required for use with ASTEP. The twenty AES weather data elements required as input to ASTEP, listed in Table 5.1, must, however, be merged in ascending order of element number for each day, and arranged chronologically over the ten year period.

A list of the stations presently available for use with ASTEP is provided in Table 5.2.

Several subroutines have been written for ASTEP to allow a high degree of flexibility, as well as low cost, when using AES data. These procedures include a third degree polynomial interpolation using Newton's forward difference formula for evenly spaced points which is used to calculate solar radiation on surfaces tilted at other than 0°, 30°, 60° and 90°.

TABLE 5.1

AES Element Number Definitions for ASTEP Weather Data

Element Number	Description
078	Dry bulb temperature (0.1°C)
	Global Radiation (kJ/m^2)
901 903 905	North facing sfc 30° 60° 90°
907 909 911	West facing sfc 30° 60° 90°
913 915 917	Southwest facing sfc 30° 60° 90°
919 921 923	South facing sfc 30° 60° 90°
925 927 929	Southeast facing sfc 30° 60° 90°
931 933 935	East facing sfc 30° 60° 90°
961	Horizontal

In addition, ASTEP has the capability to load weather data for from one day up to a full year from the simulation starting date using either any single year or two consecutive years of the available ten year database. Use of the ten year database enables one to examine the affect of year-to-year weather variations on the performance of a solar heating system.

5.2 DPW Database

The Public Works Canada database contains a single year of weather data for 46 stations in Canada. Forty-one of the stations are represented by 1971 data, while the remaining five stations are represented by either 1966, 1974, or 1975. A list of the stations and their filenames for use in ASTEP are provided in Table 5.3.

Although the source of the data provided is the Canadian Atmospheric Environment Service (AES), the data have been rewritten in a special format containing hourly values for dry bulb temperature, global radiation on a horizontal surface (RF1), and ground reflectivity.

TABLE 5.2

AES 10 Year Database (1967-76)

CITY	Met Stn #	Rad Stn #	Filename
Vancouver BC	1108447	1108487	VAN
Edmonton ALTA	3012205	3012205[1]	EDM
Winnipeg MAN	5023222	5023222	WIN
Toronto ONT(City)	6158655	6158350	TOR1
Toronto ONT(MRS)	6158655	6158740	TOR2
Montreal QUE(A)	7025250	7025250[1]	MON1
Montreal QUE(JB)	7025250	7025260	MON2
Charlottetown PEI	8300300	8300400	CHA
St. John's NFLD(A)	8403506	8403506[1]	STJ1
St. John's NFLD(W)	8403506	8403600	STJ2

[1] AES synthesized solar radiation data.

TABLE 5.3

Public Works Canada Database

CITY	YR	FILE	CITY	YR	FILE	CITY	YR	FILE
PRINCE G BC	74	PRIN	KAPUSKAS ON	66	KAPU	CHARLO NB	71	CHAR
SUMMERLA BC	71	SUMM	KINGSTON ON	71	KING	CHATHAM NB	71	CHAT
VANCOUVE BC	71	VANC	LONDON ON	71	LOND	FREDERI NB	71	FRED
VICTORIA BC	71	VICT	MUSKOKA ON	71	MUSK	MONCTON NB	71	MONC
FROBIS B NT	75	FROB	OTTAWA ON	71	OTTO	SAINT J NB	71	SJHN
RESOLUTE NT	71	RESO	SAULT ST ON	71	SAUL	CHARLOT PE	71	CHAR
EDMONTON AL	71	EDMO	SUDBURY ON	71	SUDB	HALIFAX NS	71	HALI
MEDICI H AL	71	MEDI	THUNDE B ON	71	THUN	SYDNEY NS	71	SYDN
SASKATOO SA	71	SASK	TORONTO ON	71	TORO	TRURO NS	71	TRUR
SWIFT CU SA	71	SWIF	WINDSOR ON	71	WIND	YARMOUT NS	71	YARM
URANIU C SA	71	URAN	BAGOTVIL QU	71	BAGO	GANDER NF	71	GAND
BRANDON MA	71	BRAN	MONTREAL QU	71	MONT	GOOSE NF	71	GOOS
CHURCHIL MA	75	CHUR	QUEBEC QU	71	QUEB	ST.JOHN NF	71	SJHS
THE PAS MA	71	THEP	RIVIER D QU	71	RIVI	STEPHEN NF	71	STEP
WINNIPEG MA	71	WINN	SEPT ILS QU	74	SEPT	VAL DOR QU	71	VALD
			SHERBROO QU	71	SHER			

Modelling is included in ASTEP to calculate the incident solar radiation on a tilted collector surface using RF1 as input. The models were selected on the basis of conformity with other existing simulation programs at Public Works Canada.

To estimate the solar radiation on a tilted surface, it is necessary first to process the horizontal value (RF1) to obtain the beam and diffuse components. This is calculated using a correlation by Orgill and Hollands (1977).

$$\begin{aligned} H_d &= 0.1769.H \quad (K_T > .75) \\ &= (1.55699 - 1.84013.K_T)H \quad (0.35 \leqq K_T \leqq 0.75) \\ &= (1. - 0.248857.K_T)H \quad (0.0 \leqq K_T \leqq 0.35) \end{aligned} \qquad 5.2$$

where

H = global solar radiation on a horizontal surface
H_d = diffuse solar radiation on a horizontal surface
$K_T = H/H_o$

H_o is the extraterrestrial solar radiation on a horizontal surface.

$$H_o = SC(1. + 0.033 \cos(2\pi N/365))\cos(\theta_z)$$

where,

$\cos(\theta_z) = \cos(\phi) \cos(\delta) \cos(\omega) + \sin(\phi) \sin(\delta)$
θ_z = zenith angle
SC = solar constant, 4871 kJ/m^2-hr
N = day of the year
δ = solar declination, degrees
ϕ = latitude, degrees
ω = hour angle, degrees

The value for the diffuse radiation on the horizontal surface, H_d, is then transformed to a tilted surface using an anisotropic model by Temps and Coulson (1977) and Klucher (1979).

$$I_d = \left(\frac{1 + \cos(\beta)}{2}\right)(1 + F \sin^3(\beta/2))(1 + F \cos^2(\theta_i) \cdot \sin^3(\theta_z))H_d \qquad 5.3$$

where

$$F = 1 - (H_d/H)^2$$

6.0

MODELS AND ASSUMPTIONS

ASTEP provides modelling for three basic solar heating system types, a liquid heat transport and storage fluid in conjunction with a single thermal storage tank, an air-based system with a single rock bed thermal storage arranged for reversible air flow, and another liquid transport and storage system, but incorporating two storage tanks and able to store heat on both short term and seasonal cycles. The first two system types have storages sized to provide either short term or seasonal storage. All three basic systems incorporate a heat pump option with either a single or a dual source evaporator. This chapter provides a description of the various models and assumptions included in ASTEP

6.1 Thermal Storage

Thermal storage components are confined to those that can be described as right cylindrical tanks. Single tank system designs can be modelled using either rock or liquid as the storage medium for both seasonal and short term storage applications. The dual tank option is available for liquid-based systems only.

6.1.1 Liquid Storage

The liquid storage medium is assumed to be well mixed. The user may, however, specify a pseudo-linear temperature gradient to be

used to adjust the mean storage temperature when making collector efficiency calculations. By substracting one-half of the top-to-bottom temperature difference from the mean tank temperature, the new temperature will represent the collector inlet temperature. This assumes, in effect, that the intake is located at the bottom of a linearly stratified tank.

A rejection temperature for the storage is specified by the user. When the storage exceeds this predetermined temperature, the excess heat is dumped. For Type I and Type III systems, the mean tank temperature is used as the criterion, but for Type II Systems the temperature of the top segment of the rock bed storage is taken.

For seasonal storage tanks, it is assumed that the starting time of the simulation corresponds closely with the minimum point of the annual storage temperature cycle. The initial temperature for the storage should be equal to this minimum temperature of the design annual temperature cycle.

Storage boundary heat loss calculations are separated into two classes; seasonal storage and short term storage. Tanks for short term storage are characterized as of cylindrical form. Heat loss to the surroundings is calculated neglecting thermal transients, assuming the surfaces of the insulated tank are exposed directly to the ambient air (outdoor or indoor).

Tanks for seasonal storage, being inherently larger, are characterized as of cylindrical form and below grade construction, with the tank top either flush with the ground surface or located directly below the conditioned building. Heat loss calculations for this type of tank are separated into two components; heat loss through the tank lid, and heat loss from the walls and floor through the earth surrounding the buried tank. The heat loss from the tank lid is calculated neglecting thermal transients, assuming the tank top surface of the insulated tank is exposed directly to

the ambient air (outdoor or indoor).

The heat transfer process through the soil surrounding a buried thermal storage tank is a three dimensional time transient with temperature and moisture dependent thermal and physical properties. The seasonally varying ambient air and the soil constitute the two heat sinks for the system. This system can be solved for the transient heat flux at any point and time using finite difference methods for space and time which are particularly well suited to high speed computers. An example of the nodal network for such an analsis is shown in Figure 6.1.

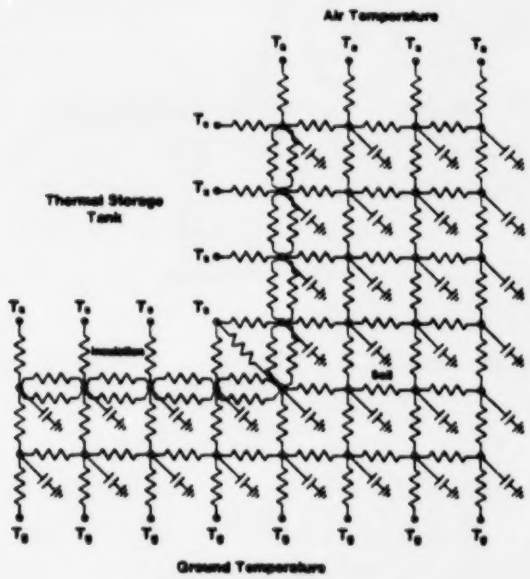


Figure 6.1 Detailed Finite Difference Representation for Thermal Analysis of a Buried Tank

By lumping the distributed parameters together, a much simpler network as shown in figure 6.2 can be applied to solve for the transient heat flux at any time.

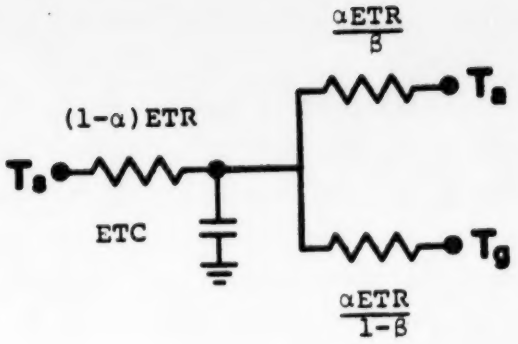


Figure 6.2 Simplified Lumped Parameter Model for Thermal Analysis of a Buried Tank

The parameters ETR and β, however, must be determined by using the more complex spatial finite difference network. The resistance to heat flow from a buried tank to the surrounding heat sinks can be divided into two parts, the contribution from the applied insulation and that from the surrounding soil. The insulating contribution of the soil is the principal unknown here, being, in effect, variable over the tank surface, corresponding to the resistances along the heat flow paths from the various points on the tank wall to the heat sinks.

The effective soil resistance for all points along the tank surface can be lumped together to produce an effective resistance for the entire soil region. This parameter depends, among other factors, on the tank shape and demensions, and the depth of the water table which is assumed to act as an isothermal heat sink. By combining the effective soil thermal resistance with the thermal resistance of the applied insulation, an effective thermal resistance (ETR) is determined for a particular tank-soil configuration. Values of the effective unit thermal resistance of the soil, R_s, used to calculate ETR and β, are presented in Appendix A for a wide range of practical tank configurations.

A description of the finite difference-in-time heat flow equations, resulting from the simplified network shown in Figure 6.2, is outlined below.

$$Q_e = \frac{(T_s - T_e)t}{(1 - \alpha)\ ETR} \qquad 6.1$$

$$Q_a = \frac{(T_e - T_a)\beta t}{\alpha . ETR} \qquad 6.2$$

$$Q_g = \frac{(T_e - T_g)\ (1 - \beta)t}{\alpha\ ETR} \qquad 6.3$$

$$T_e = T_e + \frac{(Q_e - Q_a - Q_g)}{ETC} \qquad 6.4$$

where

Q_e = heat flow from storage
Q_a = heat flow to ambient air sink
Q_g = heat flow to ground sink
T_a = ambient air temperature
T_e = earth temperature
T_g = ground sink temperature
T_s = storage reservoir temperature
t = time step
α = defines the location of the lumped thermal capacity (ETC) of the system. Calculated as

$$\alpha = 1 - \frac{R_I + \frac{1.4}{k_s}}{R_I + R_s}$$

where

R_I = unit thermal resistance of insulation
R_s = unit thermal resistance of soil

k_s = soil thermal conductivity

β = the proportion of the heat sink associated with the ambient air, evaluated at steady-state conditions (see Appendix A).

ETC = the effective thermal capacity of the surrounding soil, calculated for the soil volume bounded by the water table at the bottom and extending outward two tank radii from the tank wall.

ETR = the effective thermal resistance of the tank-soil configuration (see Appendix A).

The simplified heat loss model is particularly applicable to the seasonal storage concept. This is due to the inherent physical characteristics of such systems, in which the time intervals significant in annual heat storage cycles lead to limit cycles which are well defined by the solution to the pseudo-steady sinusoidal temperature variations in the system over a one year period. After the start-up transients, usually significant only in the first year of operation, a repeating cycle is closely approached.

Although any time dependent periodic variation can be assumed, the tank temperature (T_s) and air temperature (T_a) are taken in this case to vary sinusoidally and independently over the year. As well, the ground sink temperature (T_g) is assumed to be equal to the annual average air temperature (T_a). These assumptions are well supported for the seasonal stroage case by previous analytical and experimental studies. The initial earth temperature for the limit steady state condition is then calculated as outlined in equation 6.5.

$$T_{e,t=0} = T_{s,t=0} - (1-\alpha)\ ETR(Z_2 + D) \qquad 6.5$$

where

$$D = \frac{\bar{T}_s - \bar{T}_a}{ETR}$$

$$Z_2 = \frac{\sin\phi_s}{2ETR}\left(T_s^{max} - T_s^{min}\right) - \frac{\beta \sin\phi_a}{2ETR}\left(T_a^{max} - T_a^{min}\right) + \alpha A$$

$$A = \frac{\lambda\omega ETC}{\lambda^2+\omega^2}\left\{\frac{\alpha}{2}\left(T_s^{max} - T_s^{min}\right)\left(\lambda\cos\phi_s + \omega\sin\phi_s\right)\right.$$

$$\left. + \frac{\beta(1-\alpha)}{2}\left(T_a^{max} - T_a^{min}\right)\left(\lambda\cos\phi_a + \omega\sin\phi_a\right)\right)$$

$$\lambda = \frac{1}{\alpha(1-\alpha)ETR \cdot ETC}$$

$\bar{T}_s$ = mean annual tank temperature

$\omega = \frac{2\pi}{P}$, where P = period

ϕ_s = Starting point of sinusoidal storage temperature function

ϕ_a = starting point of sinusoidal air temperature function

6.1.2 Rock Bed

The rock bed thermal storage is operated by maintaining either a downward air flow during charging from the collector or an upward air flow to discharge stored heat to the loads. Assuming negligible temperature gradients within the rocks, uniform flow distribution of air through the bed, and a large volumetric heat transfer coefficient between the rocks and air, the partial differential equation describing both air and rock temperature as a function of position and time can be written as:

$$-A\rho_r C_r \frac{\partial T}{\partial T} = \dot{m}C_p \frac{\partial T}{\partial x} + UP(T - T_o) - kA \frac{\partial^2 T}{\partial x^2} \qquad 6.6$$

where

A = cross-sectional area of the rock bed
C_p = specific heat capacity of air
C_r = specific heat capacity of rock
k = effective thermal conductivity of the rock bed in axial direction
$\dot{m}$ = air mass flow rate
P = perimeter of rock bed wall
T = air temperature
T_o = temperature of outside environment
t = time
U = heat loss coefficient from the rock bed to the surroundings
ρ_r = apparent rock density (accounting for voids)

To solve equation 6.6, the rock bed is divided into five equal segments, numbered one to five from top to bottom. An explicit finite difference approximation reduces equation 6.6 to an ordinary differential equation for each segment.

Charge mode - internal segment i*

$$\frac{V}{N} \rho_r C_r \frac{(T_i^f - T_i)}{\Delta t} = \dot{m}C_p (T_{i-1} - T_i) - \frac{(T_i - T_o)}{R_1}$$

$$+ \frac{(T_{i-1} - T_i)}{R_2} - \frac{(T_i - T_{i+1})}{R_2} \qquad 6.7$$

* additional terms are added and/or deleted from these equations for the top and bottom segments of the rock bed.

Discharge mode - internal segment i*

$$\frac{V}{N}\rho_r C_r \frac{(T_i^f - T_i)}{\Delta t} = \dot{m}C_p (T_{i+1} - T_i) - \frac{(T_i - T_o)}{R_1}$$

$$+ \frac{(T_{i-1} - T_i)}{R_2} - \frac{(T_i - T_{i+1})}{R_2} \qquad 6.8$$

where

L = length of the rock bed in the flow direction

N = 5

R_1 = thermal resistance of tank wall segment and surroundings = (N/UPL)

R_2 = thermal resistance between segments = (L/kAN).

T_i = temperature of rock bed segment i

T_i^f = temperature of segment i at time t + Δt

V = volume of rock bed

Stratification is normally utilized in rock bed storages. Since the temperature of each segment is calculated, it is not necessary to include any arbitrary assumptions about the temperature stratification as described for liquid storage.

A rejection temperature for the rock bed storage is specified by the user. When the top segment of the rock bed storage exceeds this predetermined temperature, the excess heat is dumped.

The soil contribution to the thermal resistance factor, R_1, of buried seasonal storage tanks is calculated using the same method as presented previously for liquid storage.

* additional terms are added and/or deleted from these equations for the top and bottom segments of the rock bed.

6.2 Solar Collector

The instantaneous steady state efficiency of a solar collector (η), defined as the ratio of the rate of heat collected to that available, can be conveniently expressed using the Hottel-Whillier equation as:

$$\eta = \tau\alpha - U_L(T_c - T_a)/I \qquad 6.9$$

where

$\tau\alpha$ = optical efficiency
U_L = collector heat loss coefficient
T_c = mean collector temperature
T_a = ambient air temperature
I = solar irradiance

An example of a plot of this equation, referred to as the collector efficiency curve, is shown in Figure 6.3.

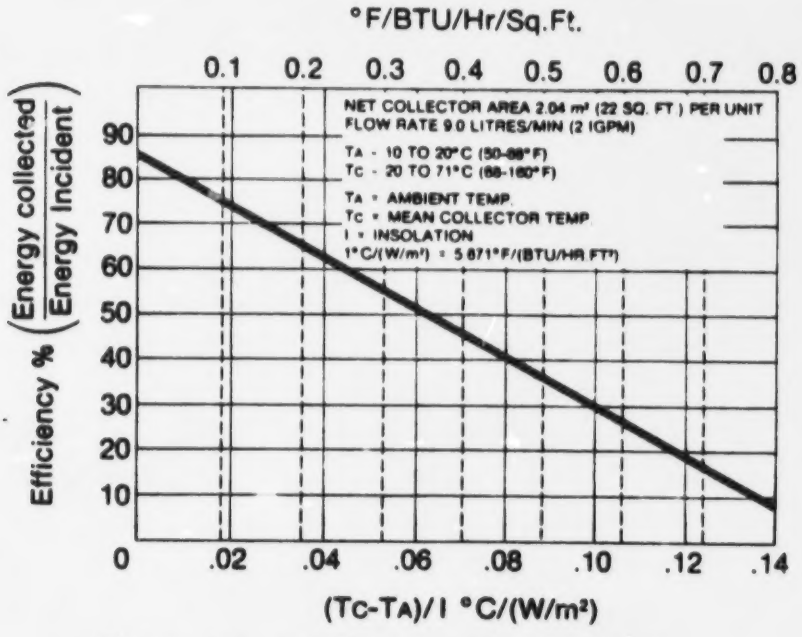


Figure 6.3 A Collector Efficiency Curve

The efficiency is plotted as the ordinate, and the collector operating point ($\Delta T/I$) is as the abscissa. The straight line is based on a statistical fit of experimental data points for a typical high efficiency single-glazed flat plate collector.

Because of the difficulty of measuring the mean collector surface temperature, the collector operating point is based on the collector inlet fluid temperature, the outlet fluid temperature, or the mean fluid temperature. The collector efficiency is then expressed as:

$$\eta = FA_{kT}\tau\alpha - FU_L(T - T_a)/I \qquad 6.10$$

where

F = heat transfer factor (F_i, F_o, F_m) depending on the use of either inlet fluid temperature, outlet fluid temperature, or mean fluid temperature to define the collector operating point.

T = inlet fluid temperature (T_i), outlet fluid temperature (T_o), or mean fluid temperature (T_m).

A_{kT}= incidence angle modifier

The y-intercept ($F\tau\alpha$) and slope ($-FU_L$) of the resulting collector efficiency curve therefore depend on the particular definition of the collector operating point.

ASTEP uses as input the slope and y-intercept of the collector efficiency curve based on the collector inlet fluid temperature, as these can be directly used in the system calculations. Techniques for transforming collector efficiency curves based on the outlet fluid temperature or the mean fluid temperature to that of the inlet fluid temperature are described by Lunde (1980). Care must be taken, when using manufacturer's data, that the proper values are used for the particular flow rates considered.

The incidence angle modifier, A_{kT}, is calculated for any value of the direct beam incidence angle using a cubic spline interpolation of the five data pairs of incidence angle and A_{kT} values supplied by the user. In addition, a heat exchanger correction factor (DeWinter 1975) is used to modify the collector performance equation to account for the effects of a heat exchanger between the collector and storage.

An option is included to allow the user to incorporate a horizontal diffuse reflector in front of the collectors. The total irradiance on the horizontal reflector surface is multiplied by a reflector configuration factor, and the result is added to the global insolation on the tilted surface to determine the total irradiance on the collector surface. A useful reference of radiant-interchange configuration factors between plane surfaces is provided by Feingold (1966).

6.3 Heating Loads

The required delivery heat to match building consumption is separated into space heating and service hot water components.

6.3.1 Space Heating

Space heating load calculations require the user to specify a heat load factor and an effective thermostat setting for the building. The heat load factor is a measure of the heat loss rate from the building for each degree temperature difference between the outside dry bulb temperature and the effective thermostat setting, and is assumed to be constant throughout the heating season defined by the user. Internal heat gains account for the difference between the effective thermostat setting and the actual thermostat setting for the building.

Below a user-specified storage temperature setting, auxiliary heating, directly, or by way of a heat pump, is initiated.

6.3.2 Service Hot Water

Service hot water load computations require that the user specify a daily mass flow rate, an hourly distribution pattern, a delivery temperature, and a make-up water temperature. The effects of a heat exchanger between storage and load are accounted for by specifying a temperature difference between storage medium and delivery temperature. These parameters are assumed to be constant throughout the year.

6.4 Auxiliary

Below some predetermined storage temperature specified by the user, auxiliary heating, directly, or by way of a heat pump, is initiated. If the heat pump option is not specified, the storage tank is assumed to be, in effect, disconnected from the delivery system, at which point, an auxiliary heating system provides the necessary back-up to meet the loads.

6.4.1 Heat Pump

The heat pump performance computations assume a linear relationship between COP and evaporator temperature. The heat pump COP at 0°C, and the slope of the heat pump COP curve versus evaporator temperature, are input by the user. An option is included to allow dual evaporators that switch the heat source between the ambient air and the storage in order to select the highest temperature heat source. Typical values of COP for a wide range of evaporator temperatures are shown in Figure 6.4.

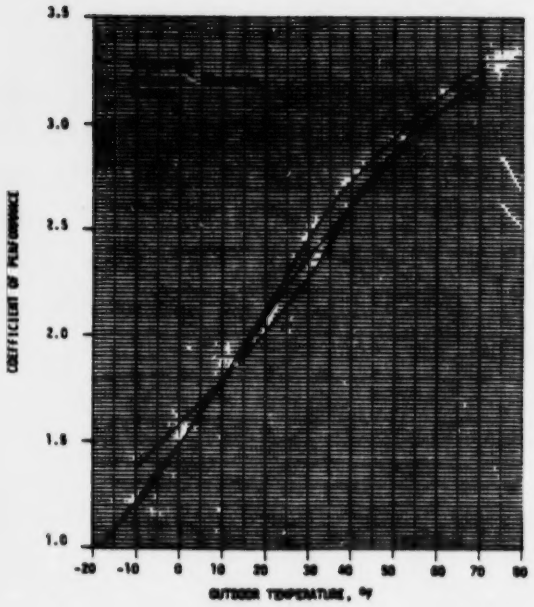


Figure 6.4 Heat Pump Heating COP

(Reproduced from Report No. HCP/M2121-01 by Gordian Ass. Inc. for the U.S. DOE, June 1978)

APPENDIX A

Precalculated Parameters for the Simplified Seasonal Storage Heat Loss Model

The parameters ETR and β, used in the simplified lumped parameter storage heat loss model shown in Figure 6.2, must be determined using a detailed spatial finite difference model. The results of such tests are presented here for a wide range of practical buried tank configurations.

The effective unit thermal resistance of the soil, R_s, normalized with tank depth, is required for calculating ETR for a particular tank-soil configuration. It is a function primarily of the soil thermal conductivity, the tank radius-to-depth ratio (R/D), the thermal resistance of the applied insulation (R_I), and the ratio of the depth of the water table to the tank depth (S/D). A large number of tests were carried out to determine R_s values for a wide range of practical tank configurations. The results are presented in Table A-1. The values tabulated are based on a tank depth of 15 m and a reference soil thermal conductivity of 1.73 W/m·K. R_s values are scaled in ASTEP to the particular tank depth and soil thermal conductivity by multiplying by the tank depth and $1.73/k_{soil}$ respectively. It is important to note that when scaling to tank depths other than 15 m, the insulation thickness and resulting R_I must be scaled as well. In other words, if an R_s value is selected for R_I = 5 and scaled by ASTEP to 30 m (R_s x 30) then the resulting soil R-value is valid for R_I = 10. Similarly, the ratio between the insulation thermal conductivity and the soil thermal conductivity must remain the same when scaling. In other words, if a particular soil thermal conductivity was twice the reference 1.73 W/m·K, and R_I = 5, then the resulting scaled R_s value in ASTEP (R_s x 1.73/3.46) is valid for R_I = 2.5. β, or beta, designates the proportion of the toal heat flow through the soil that is lost to the ambient air at the surface of the ground. Beta is a steady state constant for a particular tank-soil configuration, and is independent of the boundary temperatures. Values for β are presented in Table A-2. Scaling rules as discussed previously for R_s values also apply here.

TABLE A-1

Normalized Soil R-values ($m \cdot K \cdot W^{-1}$)

R/D	0.25				0.5				1.0				2.0			
$R_I \left(\frac{m^2K}{W}\right)$ / S/D	0	2.5	5	10	0	2.5	5	10	0	2.5	5	10	0	2.5	5	10
1.5	0.069	0.134	0.141	0.145	0.075	0.141	0.149	0.153	0.089	0.172	0.181	0.186	0.111	0.204	0.213	0.219
2.0	0.072	0.147	0.154	0.158	0.078	0.154	0.162	0.167	0.094	0.200	0.210	0.216	0.123	0.263	0.279	0.287
2.5	0.072	0.148	0.156	0.159	0.078	0.155	0.164	0.169	0.095	0.204	0.213	0.219	0.126	0.275	0.290	0.298

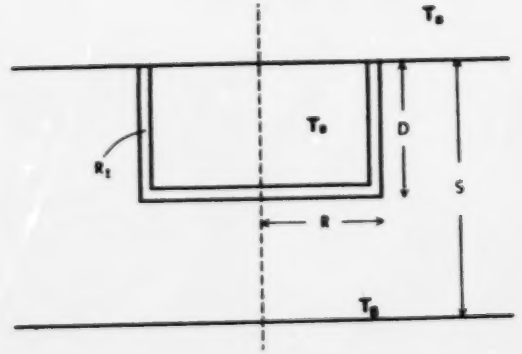
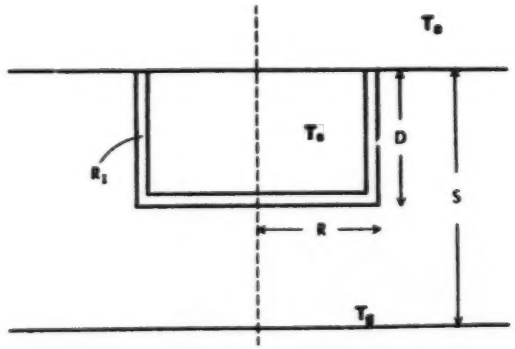


TABLE A-2

Beta Values

R/D	0.25				0.5				1.0				2.0			
R_I ($\frac{m^2 K}{W}$) / S/D	0	2.5	5	10	0	2.5	5	10	0	2.5	5	10	0	2.5	5	10
1.5	0.851	0.644	0.616	0.599	0.818	0.591	0.564	0.547	0.790	0.518	0.486	0.466	0.715	0.413	0.377	0.356
2.0	0.893	0.690	0.654	0.630	0.854	0.637	0.603	0.581	0.848	0.581	0.547	0.515	0.800	0.495	0.442	0.402
2.5	0.899	0.695	0.657	0.633	0.860	0.642	0.607	0.584	0.855	0.591	0.555	0.523	0.819	0.509	0.451	0.410



REFERENCES

Davies, J.A., and J.E. Hay 1980. Calculation of the solar radiation incident on a horizontal surface. In *Proceedings: First Canadian solar radiation data workshop*, ed. J.E. Hay and J.K. Won, 32-58. Canadian Atmosphric Environment Service and National Research Council of Canada.

Davies, J.A. 1981. *Models for estimating incoming solar irradiance*. Canadian Climate Centre Report No. 81-2, unpublished manuscript. Downsview, Ont.: Atmospheric Environment Service.

DeWinter, F. 1975. Heat exchanger penalties in double loop solar water heating systems. *Solar Energy* 17: 335-337.

Fiengold, A. 1966. Radiant-Interchange configuration factors between various selected plane surfaces. *Proc. Roy. Soc. (London)* 292: 51-60.

Hay, J.E., and J.A. Davies. 1980. Calculation of the solar radiation incident on an inclined surface. In *Proceedings: First Canadian solar radiation data workshop*, ed. J.E. Hay and J.K. Won, 59-72. Canadian Atmospheric Environment Service and National Research Council of Canada.

Hooper, F.C., C.R. Attwater, A.P. Brunger, J.A. Davies, J.E. Hay, D.C. McKay, and T.K. Won. 1979. The Canadian solar radiation data base. *ASHRAE Trans.* 85(2): 497-506.

Klucher, T.M. 1979. Evaluation of models to predict insolation on tilted surfaces. *Solar Energy* 23: 111-114.

Lunde, P.J. 1980. *Solar thermal engineering*. J. Wiley & Sons.

McKay, D.C., and T.K. Won. 1979a. Expansion of the Canadian solar radiation data base by estimation. *Proc. Sol. Energy Soc. Canada* 2:

McKay, D.C., and T.K. Won. 1979b. The estimation of solar radiation on various tilted surface and azimuths. *Proc. Sol. Energy Soc. Canada* 2:

Orgill, J.F., and K.G.T. Hollands. 1977. Correlation equation for hourly diffuse radiation on a horizontal surface. *Solar Energy* 19:

Temps, R.C., and K.L. Coulson. 1977. Solar radiation incident upon slopes of different orientation. *Solar Energy* 19: